

ON THE SURVIVAL OF BROWN DWARFS AND PLANETS ENGULFED BY THEIR GIANT HOST STAR

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ABSTRACT

The recent discovery of two Earth-mass planets in close orbits around an evolved star has raised questions as to whether substellar companions can survive encounters with their host stars. We consider whether these companions could have been stripped of significant amounts of mass during the phase when they orbited through the dense inner envelopes of the giant. We apply the criterion derived by Murray et al. for disruption of gravitationally bound objects by ram pressure, to determine whether mass loss may have played a role in the histories of these and other recently discovered low-mass companions to evolved stars. We find that the brown dwarf and Jovian mass objects circling WD 0137-349, SDSS J08205+0008, and HIP 13044 are most unlikely to have lost significant mass during the common envelope phase. However, the Earth-mass planets found around KIC 05807616 could well be the remnant of one or two Jovian mass planets that lost extensive mass during the common envelope phase.

Subject headings: planetary systems — binaries: close — stars: evolution — stars: low-mass, brown dwarfs — stars: individual (KIC 05807616)

1. INTRODUCTION

The question of survivability of planets during post-main-sequence evolution of the host star has attracted some interest over the past years (Villaver & Livio 2007; Nordhaus et al. 2010; Spiegel 2012). Recently, many substellar companions have been discovered in close orbits around evolved stars (Table 1). Maxted et al. (2006) detected a 0.053 M_⊙ brown dwarf orbiting the 0.39 M_⊙ white dwarf WD 0137-349 with a 1.9-hour period. A likely brown dwarf was discovered in a 2.3-hour orbit around the subdwarf B star SDSS J08205+0008 (Geier et al. 2011). Setiawan et al. (2010) discovered a Jupiter-mass object orbiting the red horizontal branch star HIP 13044 with a 16.2-day period. Finally, Charpinet et al. (2011) reported the detection of two nearly Earth-sized planets orbiting the subdwarf B star KIC 05807616 with orbital periods of 5.8 and 8.2 hours. The existence of these systems for which the radius of the precursor of the primary was larger than today's orbital separation, suggests that they have gone through a common envelope (CE) interaction. During this phase, the companion is engulfed by its host star's envelope when the latter was a giant star (Paczynski 1976).

Hydrodynamics simulations of this evolutionary phase have been performed with different numerical techniques (Sandquist et al. 1998; Passy et al. 2012; Ricker & Taam 2012) but questions persist. It is still unclear how the envelope of the donor star gets ejected, and why the final separations obtained by simulations are larger than those observed in post-CE systems (Passy et al. 2012). The resolution reached in these numerical models currently does not suffice to study the complete evolution for a substellar companion that may spiral down to very close

to the giant's core.

An important question is therefore whether substellar companions can survive engulfment by the giant's envelope without being totally disrupted. A system with a very low mass companion has a very small orbital energy budget, so we may also plausibly conjecture that a CE in such a system would more likely fail and result in a merger, thus destroying the companion. Is it therefore possible that substellar companions started off as more massive objects, which were then partially disrupted during their engulfment to become the objects we see today? This scenario was actually suggested by Charpinet et al. (2011) to explain the existence of planets around KIC 05807616.

Murray et al. (1993) studied the disruption of gravitationally bound objects by direct action of ram pressure in the context of star formation and galaxy evolution. However the physics of disruption is scale free, so their results also apply to other astrophysical questions such as the gas stripping occurring in clustered galaxies (Nulsen 1982; Mori & Burkert 2000) or here, the disruption of hydrostatic companions captured by the envelope of a giant star. In this contribution we use their theory to determine whether, in the observed systems, the substellar companions could have lost a significant amount of mass during the in-spiral phase. We describe the formalism used in Section 2 and present the results in Section 3. We provide a summary in Section 4.

2. ANALYSIS

Murray et al. (1993) calculated the conditions for a self-gravitating, hydrostatic, isothermal sphere moving in an ambient medium to be disrupted by ram pressure. The disruption of an object by ram pressure can most simply be understood by the pancake model (Zahnle 1992; Klein et al. 1994), in which transverse motions are driven by the increased pressure on the front surface of the object compared to the sides. Field & Ferrara (1995) showed that the actual disruption by Kelvin-Helmholtz and Rayleigh-Taylor instabilities with wavelengths com-

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parable to the size of the object reproduces the scalings yielded by this simple model. Murray et al. (1993) confirmed numerically that when self-gravity is strong enough to stabilize the Kelvin-Helmholtz instability, the sphere is stable against catastrophic disruption. This occurs when the gravitational acceleration

$$g \gtrsim g_{\text{crit}} \equiv \frac{2\pi\rho_2\rho_1 U^2}{R_2(\rho_2^2 - \rho_1^2)} \quad , \quad (1)$$

where ρ_1 , ρ_2 , R_2 and U are the background density, and the density, radius and relative velocity of the companion, respectively. We assume the tidal forces exerted by the giant star on the companion to be negligible compared with the self-gravity of the companion – we discuss this point in Section 3.4.1. Assuming $D \equiv \rho_2/\rho_1 \gg 1$ and taking the gravitational acceleration $g \approx GM_2/R_2^2$, one obtains a critical mass under which disruption occurs (their equation 2.8):

$$M_{\text{crit}} \sim 9.4 \left(\frac{50}{D}\right)^2 \left(\frac{U}{100 \text{ km s}^{-1}}\right)^3 \times \left(\frac{10^{-4} \text{ g cm}^{-3}}{\rho_1}\right)^{1/2} M_{\text{J}}. \quad (2)$$

If the configuration is unstable ($M_2 \lesssim M_{\text{crit}}$), the companion is disrupted in a crossing time as the characteristic timescale for destruction is equivalent to its internal dynamical timescale:

$$\tau \sim 1.4 \left(\frac{R_2}{0.1 R_{\odot}}\right) \left(\frac{100 \text{ km s}^{-1}}{U}\right) \left(\frac{D}{50}\right)^{1/2} \text{ hr}. \quad (3)$$

We approximate the relative velocity of the companion by the maximum orbital velocity reached during the in-spiral phase, i.e. the final orbital velocity:

$$U \sim \sqrt{\frac{GM_c}{a}} \quad (4)$$

where $M_c \gg M_2$ is the mass of the primary's core, and a is the orbital separation at the end of the CE phase. We substitute this relation in Equation (2), and obtain the critical background density above which the companion is unstable:

$$\rho_{1,\text{crit}} \sim 1.4 \cdot 10^{-3} \left(\frac{a}{R_{\odot}}\right) \left(\frac{M_{\odot}}{M_c}\right) \left(\frac{M_2}{M_{\text{J}}}\right)^{2/3} \times \left(\frac{\rho_2}{1 \text{ g cm}^{-3}}\right)^{4/3} \text{ g cm}^{-3}. \quad (5)$$

One should emphasize that if the companion is unstable, the dominant wavelength acting to destroy it is comparable to the sphere radius. The destruction is therefore global and not quasi-static. In other words, the companion is destroyed catastrophically, not ablated by incremental mass-loss due to short wavelength surface instabilities. Thus stability cannot be reached again once disruption starts.

If the companion is stable ($M_2 \gtrsim M_{\text{crit}}$), such shorter wavelength instabilities can still occur and strip mass in a more ablative manner, giving a quasi-static mass loss

rate. We compute the largest unstable wavelength from Equations (1) and (4), again assuming $\rho_2 \gg \rho_1$, and substituting λ_{max} for R_2 . We find

$$\lambda_{\text{max}} = 7.8 \cdot 10^{-2} \left(\frac{M_c}{M_{\odot}}\right) \left(\frac{R_{\odot}}{a}\right) \left(\frac{1 \text{ g cm}^{-3}}{\rho_2}\right)^{5/3} \times \left(\frac{\rho_1}{10^{-4} \text{ g cm}^{-3}}\right) \left(\frac{M_{\text{J}}}{M_2}\right)^{1/3} R_{\text{J}}. \quad (6)$$

Murray et al. (1993) suggests that the corresponding mass loss rate can then be approximated to that occurring in laminar viscous flows as described by their Equation 3.5:

$$\dot{M}_{\text{v}} \sim 11 \left(\frac{U}{100 \text{ km s}^{-1}}\right) \left(\frac{\rho_1}{10^{-4} \text{ g cm}^{-3}}\right) \times \left(\frac{R_2}{0.1 R_{\odot}}\right)^2 \left(\frac{\lambda_{\text{max}}}{R_2}\right) M_{\text{J}} \text{ yr}^{-1} \quad (7)$$

where we have assumed the relative velocity to be of the order of the sound speed of the background. Equation (7) should be used with caution as it is valid only for Reynolds numbers $Re \lesssim 30$ (Nulsen 1982). In our case, the Reynolds number is $Re = 2R_2U/\nu$, where ν is the molecular viscosity. Viscosity in stellar interiors is far too small to allow such low Reynolds numbers on these length scales.

However, such low effective Reynolds numbers might be reached through the turbulent viscosity. Since the largest possible size of the eddies is λ_{max} and their largest velocity is the sound speed of the ambient medium c_s , one can use a formalism like that of Shakura & Sunyaev (1973) and parametrize the turbulent viscosity as:

$$\nu_{\text{t}} = \alpha c_s \lambda_{\text{max}} \quad (8)$$

where $\alpha \lesssim 1$ is a free parameter. The effective Reynolds number is thus:

$$Re_{\text{t}} \sim \frac{2R_2}{\alpha \lambda_{\text{max}}} \quad (9)$$

where we have still assumed that $U \sim c_s$. Unfortunately, no accepted value of α has been derived for our specific case. We can only calculate the minimum turbulent Reynolds number $Re_{\text{t,min}} = Re_{\text{t}}(\alpha = 1)$ and see how this number compares to the range required to apply Equation (7).

Another approach would be to calculate how much work from the drag acts on the companion during its in-spiral, and compare it to the companion's gravitational binding energy $E_{\text{bin}} \sim GM_2^2/R_2$. Assuming for the cross section $S_2 = \pi R_2^2$ and a drag coefficient C_D , the drag force is $F_D = \frac{1}{2} C_D \rho_1 U^2 S_2$. The smaller the companion, the longer the in-spiral phase lasts: for example, the $0.9 M_{\odot}$ and $0.1 M_{\odot}$ companions complete about 20 and 40 orbits during this phase, respectively (De Marco et al. 2012; Passy et al. 2012). We therefore assume that our companions complete at least 50 orbits, and slice the giant's envelope down to the currently observed separation of the system, in $N_{\text{orbits}} = 50$ equally-spaced radii \bar{R}_i cor-

responding to an average density $\bar{\rho}_i$. Assuming $C_D = 1$, the work provided by drag forces is thus:

$$W_{\text{drag}} = \sum_{i \leq N_{\text{orbits}}} \frac{1}{2} \bar{\rho}_i U_i^2 S_2 \times 2\pi \bar{R}_i. \quad (10)$$

where $U_i = \sqrt{GM_i/\bar{R}_i}$ and M_i is the mass enclosed within \bar{R}_i . We will see in Section 3.4 that the calculation of W_{drag} does not depend strongly on the number of assumed orbits. If $W_{\text{drag}} \gtrsim E_{\text{bin}}$ we conclude that the companion could have been destroyed if the drag energy can be coupled to the interior of the companion efficiently, even if it is stable according to Equation (1).

3. RESULTS

In this section we study each system reported in Table 1 separately and investigate whether the substellar components are less massive today than they were prior to the CE evolution.

3.1. WD 0137-349

Using the *MESA* stellar evolution code (Paxton et al. 2011), we compute a model for the $0.053 M_{\odot}$ brown dwarf companion to this white dwarf and obtain a radius $R_2 = 0.079 R_{\odot}$ (Figure 1). The mean density of the brown dwarf is $\rho_2 = 150 \text{ g cm}^{-3}$ which, substituted in Equation (5), yields a critical density $\rho_{1,\text{crit}} \approx 27 \text{ g cm}^{-3}$.

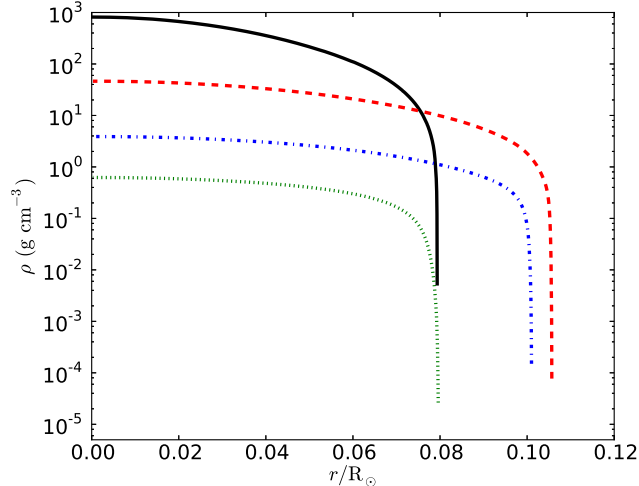


FIG. 1.— Density profiles for the $0.053 M_{\odot}$ (solid black), $10 M_J$ (dashed red), $1 M_J$ (dash-dotted blue) and $0.1 M_J$ (dotted green) models.

We compare this critical density to the density profile of the progenitor and see whether the companion will plunge deep enough into the primary’s envelope to encounter a density high enough to destroy it. The most likely progenitor of the white dwarf is a nearly $1 M_{\odot}$ main sequence star. We evolve such a model with *MESA* up to the red giant branch until the core mass reaches the observed white dwarf mass. At that time, the radius of the star was $100 R_{\odot}$ and its total mass was $0.89 M_{\odot}$ due to mass loss. The density profile of this red giant

star is displayed in Figure 2. The current orbital separation of the system is $a = 0.65 R_{\odot}$ which means that the companion has reached a layer of the primary where the density $\rho_{1,\text{max}} \sim 2.1 \times 10^{-3} \text{ g cm}^{-3}$.

At this point, we should emphasize that we have calculated the maximum density encountered by the companion using the *initial* profile of the giant primary. Hydrodynamical simulations suggest that in the deep interior, density at a given coordinate decreases with time (Passy et al. 2012, Figure 12) although the current resolution does not allow them to give a definitive answer at such small radii. Therefore, $\rho_{1,\text{max}}$ should be considered an upper limit.

$\rho_{1,\text{max}}$ is four orders of magnitude smaller than the critical density required for instability so we conclude that the companion is stable. Moreover, the mass loss rate due to viscous stripping $\sim 3.8 \times 10^{-2} M_J \text{ yr}^{-1}$ only. Since the dynamical phase of a CE lasts only about one year (Sandquist et al. 1998; Passy et al. 2012), the companion has not lost any significant amount of mass during its in-spiral phase.

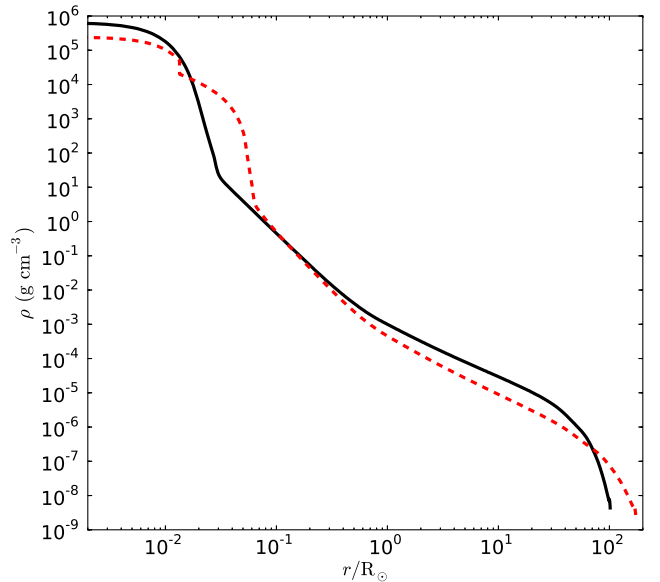


FIG. 2.— Density profile for the $0.89 M_{\odot}$ red giant star progenitor of WD 0137-349 (solid black) and a $0.76 M_{\odot}$ star at the tip of the red giant branch (dotted red).

3.2. SDSS J08205+0008

SDSS J08205+0008 is very similar to WD 0137-349 so we also conclude that the brown dwarf – whose estimated mass ranges from 0.045 to $0.068 M_{\odot}$ – has not been affected during the plunge-in phase.

3.3. HIP 13044

The minimum mass of the planet orbiting HIP 13044 is estimated to be $1.25 M_J$ (Setiawan et al. 2010). This system is intriguing, as a plausible formation channel for this system has yet to be found. Indeed, the orbital separation ($\sim 25 R_{\odot}$) is much larger than the

separations obtained from numerical simulations or observations of post-CE systems (De Marco et al. 2011; Passy et al. 2012). Also, successful CE interactions usually lead to the formation of blue horizontal branch stars with very thin hydrogen-envelopes (Han et al. 2002).

Bear et al. (2011) therefore suggested that the helium flash occurring in a $0.9 M_{\odot}$ metal-poor red giant star could ignite hydrogen burning in a thick region at the bottom of the envelope. This deposition of energy would eventually lead to a dramatic inflation lasting about 100 yr, during which the stellar radius could reach $700 R_{\odot}$. The planet would then enter a “half-failed, half-successful” CE during which the orbital separation would shrink down to approximately $25 R_{\odot}$, only $0.1 M_{\odot}$ would be lost by the system and the primary would evolve to the red part of the horizontal branch.

This theory has several problems. First, there is no compelling evidence suggesting that red giant branch stars might suffer such a large and long-lasting expansion after the helium core flash. On the contrary simulations performed with stellar evolution codes such as *MESA*, show that red giant stars shrink after helium has been ignited explosively. Secondly, the duration of this suggested post-helium-flash expansion is larger than the duration of a CE phase. Therefore, the in-spiral of the companion could not have been stopped because of the primary contracting below its Roche lobe on a short timescale. Thus, the entire envelope must have been lifted up, mostly in the equatorial plane (Passy et al. 2012; Ricker & Taam 2012), which raises thus the question of how a red horizontal branch star could eventually form. Finally, the planetary companion would strongly interact with falling back material through gravitational drag. In that regard, the large orbital separation observed is still perplexing. For all these reasons we believe that the scenario suggested by Bear et al. (2011) is unlikely.

A careful investigation of the progenitor of HIP 13044 seems quite complex and beyond the purposes of this paper. Consequently we simply assume that the companion went through a CE interaction with an unknown progenitor. For the latter, we will consider the same profile as in Section 3.1 in order to give an indicative answer on the potential survival of the companion.

For the companion, we consider a $1 M_J$ model (Figure 1), with a radius $R_2 = 0.101 R_{\odot}$ and a mean density $\rho_2 = 1.31 \text{ g cm}^{-3}$. We find the critical density for stability $\rho_{1,\text{crit}} \sim 6.2 \times 10^{-2} \text{ g cm}^{-3}$. The density in the progenitor’s profile corresponding to the observed separations between the subdwarf and the planet $\rho_{1,\text{max}} \sim 10^{-5} \text{ g cm}^{-3}$, almost 4 orders of magnitude smaller than $\rho_{1,\text{crit}}$. We thus conclude that the companion is stable. The viscous mass loss rate is also negligible ($\dot{M}_v \sim 1.4 \times 10^{-4} M_J \text{ yr}^{-1}$) so no mass will be ablated from the companion during the plunge-in phase.

3.4. KIC 05807616

The most intriguing system is certainly KIC 05807616, which has two nearly Earth-mass planets orbiting a subdwarf B star with an orbital separation of about $1.5 R_{\odot}$. In order to constrain the mass of these planets prior to their engulfment, we use the same method as previously, with four different models ranging from $10 M_J$ down to

$1 M_{\oplus}$ (Figure 2). For the Earth-sized model, we use the accepted values for the Earth (see, e.g., Cox 2000) as listed in Table 2. We again assume the primary used in Section 3.1 for which we obtain $\rho_{1,\text{max}} \approx 10^{-3} \text{ g cm}^{-3}$.

The results are summarized in Table 2. One can see that the critical density required to catastrophically destroy an Earth-sized companion is about as large as the maximum density $\rho_{1,\text{max}}$. In this regard, the $1 M_{\oplus}$ companion could still be stable. However $W_{\text{drag}} \sim 10^{41}$ ergs, which is more than an order of magnitude larger than the gravitational binding energy of the companion (Table 2). W_{drag} does not strongly depend on the number of assumed orbits since changing this number to 20 or 100 changes W_{drag} by a factor 2–3 only. Since the work provided by drag forces exceeds the binding energy of the companion, we conclude that the Earth-sized companion may not survive the engulfment, if the energy can be effectively coupled to the planetary material.

From the same considerations, a $10 M_J$ companion is too massive to be affected in any way during its in-spiral phase (Table 2). For a $1 M_J$ companion, $\rho_{1,\text{max}}$ exceeds $\rho_{1,\text{crit}}$ by almost an order of magnitude, so the secondary could be stable. However, E_{bin} exceeds W_{drag} by only a factor of 3, which suggests that a significant amount of mass could be removed from the surface of the companion. A $0.1 M_J$ companion has a critical density an order of magnitude smaller than $\rho_{1,\text{max}}$. Moreover, W_{drag} is about twenty times larger than the binding energy of the companion. Together, these suggest that an $0.1 M_J$ object probably would be destroyed. Using a more evolved model with a higher core mass $M_c = 0.47 M_{\odot}$ and $N_{\text{orbits}} = 100$ (the stellar radius $\sim 175 R_{\odot}$) yields similar results (Figure 2, Table 2). We thus conclude that the progenitor of the planets likely had a mass of a few M_J , supporting the suggestion made by Charpinet et al. (2011).

3.4.1. Discussion

A legitimate question is whether mass accretion by the substellar companion is relevant. From a Bondi-Hoyle analysis (see, e.g., Edgar 2004, equation 31) the accretion rate onto the $1 M_J$ object is only

$$\dot{M}_{\text{acc}} \sim \frac{\pi G^2 M_2^2 \rho_{1,\text{max}}}{\sqrt{2} U^3} = 3.7 \times 10^{-2} M_J/\text{yr}. \quad (11)$$

We therefore conclude that mass accretion is negligible on the timescale of the CE interaction. Ricker & Taam (2008) also reached this conclusion in the case of more massive secondaries. They further argued that the mass accretion rate calculated from their simulations is even smaller than the one given by Equation (11), mainly because tidal effects dominate the structure of the flow.

Bear & Soker (2012) propose a slightly different scenario for the formation of the two planets around KIC 05807616. Instead of considering the dynamical effects occurring during the CE phase, they suggest that a massive giant planet was tidally destroyed after the end of the in-spiral phase and that the two planets are remnants of the disrupted metallic core. Using their equation 1 with $C_{\text{tide}} = 1$, the values given by Charpinet et al. (2011), and our planetary models (Table 2), the tidal radius at which destruction occurs is $R_t = 0.39$ and $0.80 R_{\odot}$ for

TABLE 1
ORBITAL PARAMETERS.

Name	M_c (M_\odot)	M_2	P	a (R_\odot)	References
WD 0137-349	0.39	55.6 M_J	1.93 hours	0.65	Maxted et al. (2006)
SDSS J08205+0008	0.25-0.47	47.1 – 71.2 M_J	2.30 hours	0.60 – 0.72	Geier et al. (2011)
HIP 13044	0.8	$\geq 1.25 M_J$	16.2 days	24.95	Setiawan et al. (2010)
KIC 05807616	0.496	0.440 M_\oplus	5.7625 hours	1.290	Van Grootel et al. (2010); Charpinet et al. (2011)
KIC 05807616	0.496	0.655 M_\oplus	8.2293 hours	1.636	Van Grootel et al. (2010); Charpinet et al. (2011)

NOTE. — Reported are the stellar mass (M_c), the companion mass (M_2), the orbital period (P) and the orbital separation (a)

the 10 and 1 M_J objects, respectively. These qualitative values are still smaller than the observed separations of the planets (see Table 1) so it is difficult to conclude whether these objects would be tidally destroyed. They also suggest that evaporation of the companion due to heating from the envelope might be important. They estimate the mass of the planet must be $\gtrsim 5 M_J$ in order to survive evaporation. The evaporation timescale depends on the efficiency of heat transfer, which is sensitive to mixing between the planetary atmosphere and the stellar convective envelope. We cannot at present calculate this timescale with sufficient precision. We therefore do not know whether evaporation could dominate the dynamical effects we discuss in this study. Nevertheless, the mass of the progenitor suggested by Bear & Soker (2012) is consistent with ours.

4. SUMMARY

We have considered evolved stars found to have brown dwarfs or planets around them in close orbits, suggesting that these systems have gone through a CE interaction. Using the criterion developed by Murray et al. (1993), we have investigated the stability of these substellar com-

panions against mass loss induced by Kelvin-Helmholtz and Rayleigh-Taylor instabilities.

We have found that the substellar companions observed in WD 0137-349, SDSS J08205+0008 and HIP 13044 are very unlikely to have been affected during the in-spiral inside their giant progenitors. Therefore, the masses of these objects currently observed are likely the same as prior to the CE phase. The two planets detected orbiting KIC 05807616, however, are not massive enough to have survived the engulfment unscathed. We have estimated the mass of the progenitor of these planets to be of order 1 M_J . The question that still has to be answered is how such low mass companions could have successfully unbound the entire envelope of the primary.

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TABLE 2
PARAMETERS OF THE DIFFERENT COMPANION MODELS INVESTIGATED FOR KIC 05807616.

M_2	R_2 (R_\odot)	ρ_2 (g.cm^{-3})	$\rho_{1,\text{crit}}$ (g.cm^{-3})	λ_{max}/R_2	$Re_{t,\text{min}}$	\dot{M}_v ($\text{M}_J \text{ yr}^{-1}$)	W_{drag} (ergs)	E_{bin} (ergs)
10 M_J	0.106	11.4	0.5	2.0(−3)	9.9(2)	0.6	1.2(43)	3.3(45)
1 M_J	0.101	1.31	6.0(−3)	1.7(−1)	12	45	1.1(43)	3.4(43)
0.1 M_J	0.080	0.27	1.5(−4)	—	—	—	7.0(42)	4.3(41)
1 M_\oplus	9.16(−3)	5.52	8.8(−4)	—	—	—	1.1(41)	3.7(39)
10 M_J	0.106	11.4	0.5	1.0(−3)	2.0(3)	0.15	5.3(42)	3.3(45)
1 M_J	0.101	1.31	6.0(−3)	8.4(−2)	24	12	4.8(42)	3.4(43)
0.1 M_J	0.080	0.27	1.5(−4)	—	—	—	3.0(42)	4.3(41)
1 M_\oplus	9.16(−3)	5.52	8.8(−4)	—	—	—	4.9(40)	3.7(39)

NOTE. — Values obtained with the 0.89 M_\odot (top) and the 0.76 M_\odot (bottom) models. Quantities relative to viscous stripping are not calculated when the object is found unstable.